METHODS TO REDUCE THE ELECTRON BEAM ENERGY SPREAD AT THE S-DALINAC*

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Abstract

The S-DALINAC is a recirculating superconducting electron linac operating at 3 GHz. The accelerator delivers a cw beam with energies up to 130 MeV to serve electron scattering experiments where highest momentum resolutions, typ. below 10^{-4} and excellent beam qualities are required. Current activities aim to reduce the energy spread of the beam of the accelerator by two methods:

Long term drifts, mainly a result of temperature drifts, will be corrected by a feedback system which measures the energy variation of the extracted beam continuously using rf monitors. By means of time-of-flight analysis in a modified beamline a correction signal can be generated as a feedback for the rf control of the accelerating cavities. This system was set-up recently and first results will be reported.

Furthermore, the influence of short term fluctuations, e.g. triggered by microphonics, on the electron energy can significantly be reduced utilizing the inherent stability of a microtron if the synchronous phase and longitudinal dispersion are chosen properly. The concept, particle simulations and the experimental verification will be shown as well as necessary modifications to the recirculation scheme to use it in an all-day operation.

INTRODUCTION

The superconducting recirculating electron accelerator S–DALINAC [1] is designed to deliver a continuous wave (cw) electron beam for nuclear and radiation physics experiments and has commenced operations in 1991. It provides an electron beam with an average current of up to 60 µA at energies of up to 130 MeV. The layout of the machine is shown in fig. 1. The injector consists of a 10 MeV linac, equipped with two superconducting 20-cell elliptical cavities and a 5-cell capture cavity, each operated at 3 GHz. After a 180° bend, the beam enters the main linac where it is accelerated with a voltage up to 40 MV. The S-DALINAC features two recirculation paths so the beam can use this voltage three times before it is extracted to the experiments.

A variety of nuclear physics experiments require the development of a new photo-injector gun to deliver polarized electrons (see [2]) as well as the increase of the energy resolution and long-term stability, which will be the focus of this paper.

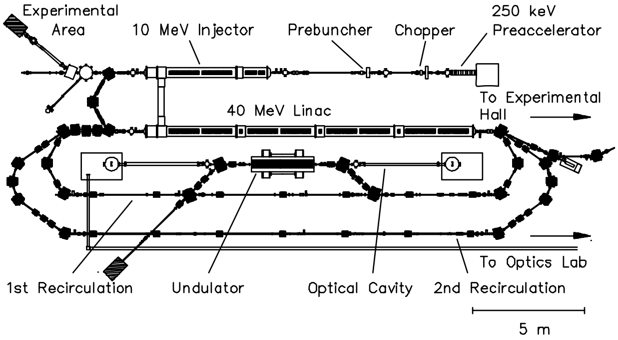

Figure 1: Layout of the superconducting recirculating electron linac S-DALINAC.

LONG TERM STABILITY

Nuclear physics experiments usually ask for constant beam energy over several weeks. This results in hard constraints for the long term stability. Energy drifts at the S-DALINAC are mainly caused by temperature variations (up to 5° C within 24 hours) and their impact on the rf control system. Currently, these drifts are adjusted manually by the operator.

After several years of operation it is necessary to design a self adjusting system. This requires a steady, non-destructive beam diagnostic. Therefore, non-invasive beam monitors were developed consisting of two rf-resonators, one is designed in the TM010 mode to give an intensity reading and the other in the TM110 mode for measuring the position. To control the energy drifts, two intensity monitors are used. The first monitor serves as a reference monitor for the beam leaving the linac. After amplification and filtering, the rf phase of this monitor is

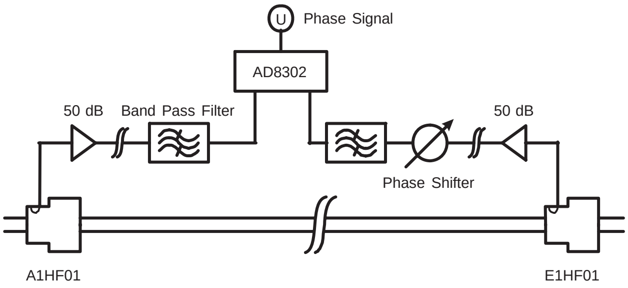

Figure 2: Measurement set-up to detect flight time shifts using non-destructive diagnostics. The AD8302 gives a signal proportional to the phase difference at its inputs.

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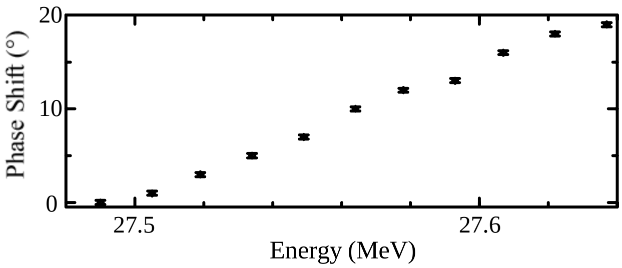

Figure 3: Measured phase shift (i.e. flight time difference) as a function of initial beam energy.

compared to the phase signal of a second monitor placed downstream in the extraction beamline. The arrangement is shown in fig. 2.

Between the two monitors, the phase difference is adjusted to zero by the phase shifter for a beam at reference energy. From a detected phase difference between the monitors the flight time difference caused by energy variations ($\Delta\delta$) can be determined, if the beamline optics provide a longitudinal dispersion (r_{56}):

$$\Delta\varphi = \frac{360°}{\lambda} r_{56}\Delta\delta \cdot \qquad (1)$$

To yield a small beam energy spread, two new quadrupole magnets were inserted recently, increasing the longitudinal dispersion from formerly 6 mm/% to now 11 mm/% without spoiling the transversal properties.

With this modified beamline the analysing power of the set-up was determined. The accuracy of the phase detector itself was measured to be 0.3° at 3 GHz. As reference beam energy E_0 = 27.55 MeV was chosen. This energy was changed in several small steps and the changes in time of flight were measured, the results are shown in fig. 3.

The relative energy resolution of this time of flight analysing system was measured to be $6*10^{-5}$. The plotted data shows a linear system response which is interesting for the later application in a control loop. In that loop, the measured phase shift is converted into a dc voltage and then digitized. Based on digital technology, the newly designed second generation rf control system will be able to use this parameter as a feedback signal.

REDUCED ENERGY SPREAD

The principle of phase focusing in longitudinal phase space is well known and is essential for the operation of circular machines like synchrotrons and microtrons. Recirculating linacs with only a few separate recirculations, however, like the S-DALINAC, are usually operated with an isochronous beam transport system and on-crest acceleration. The energy spread in that case is determined by the bunch length and the stability of the rf field in the accelerating cavities. This results in a minimum energy spread if no distortions are present but offers no stability.

As pointed out in [3] the choice of an off-crest synchronous phase together with a non-isochronous beam transport system can offer a longitudinal stability, thus reducing the effects of amplitude and phase jitter of the accelerating cavities in the linac.

A simulation of the S-DALINAC with two recirculations and three passes through the linac by simple tracking of the longitudinal phase space was carried out. A relativistic electron beam coming out of the injector uniformly distributed in longitudinal phase space with an energy spread of ± 0.1 % and a bunch length of 2° with respect to the rf-period was assumed. The eight cavities of the main linac were simulated to have an uncorrelated field amplitude jitter of 10^{-3} and a phase jitter of ± 1°, which is approximately the accuracy of the rf control loops. The longitudinal phase space distribution was calculated at the exit of the linac after three passes as a function of the synchronous phase ϕ_s and the longitudinal dispersion of the recirculating beam transport system described by r_{56}. The calculated beam energy spreads are marked on the plots in fig. 4.

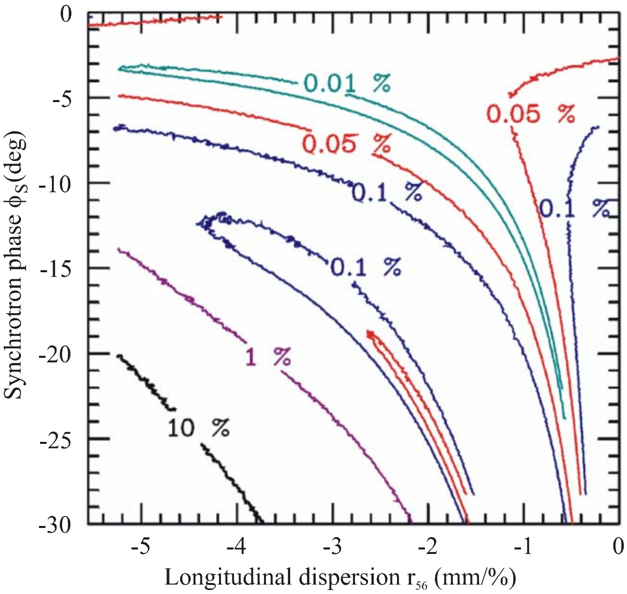

Figure 4: Calculated energy spread of the electron beam ($\Delta E/E$) as a function of the longitudinal dispersion r_{56} and the synchrotron phase ϕ_s.

The simulations showed that under these assumptions a factor of four in energy spread compared to isochronous recirculation can be gained by choosing a working point of ϕ_s = -9.7° and r_{56} = -1.5 mm/% (see fig. 4). The remaining energy spread is mainly caused by the injected beam, while the contribution of amplitude and phase jitter in the linac becomes almost negligible. The improvement concerning the energy spread of the beam delivered to the experiment can be seen in fig. 5 where the longitudinal phase space of the isochronous and the optimum non-isochronous mode are compared.

The explanation of this energy stabilisation effect is quite simple: Even though the amplitude and phase of all cavities might jitter around the reference values, mainly caused by microphonics, these deviations are slow, having typically frequencies up to some kHz. This determines the time constant of the rf-system to be around 100 μs. On the other hand the electron beam passes through all the recirculations (60 m) with the speed of light, leaving the machine within 200 ns. Simply speaking these electrons are too fast to see any changes in the rf field (being wrong but stable wrong). The optics at the working point now assures that the errors in the accelerating rf field after three linac passes cancel each other.

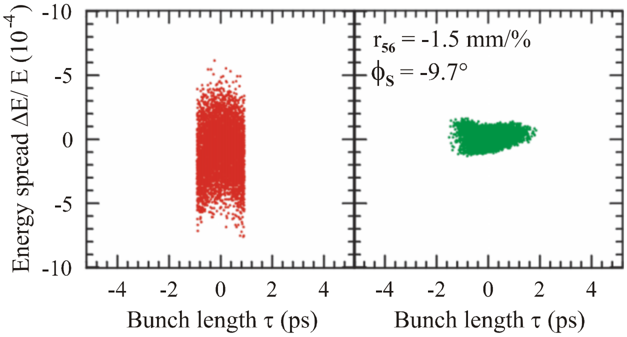

Figure 5: Calculated longitudinal phase space of the electron beam for the isochronous (left) and non-isochronous (right) mode with the optimum parameters given above.

For a test experiment, the accelerator was set-up isochronously with on-crest acceleration. Before the energy spread of the beam with energy E_0 = 81.1 MeV was measured the beam passed an analysing system with an adjustable scraper gap in a dispersive section. This allows the removal of particles outside a certain energy interval. The energy spread of the remaining beam was measured with a high resolution (10^{-4}) spectrometer via elastic scattering on a thin target. The results are shown in fig. 6: By increasing the scraper gap the transmission through the analysing system increases, according to this the energy spread increases (isochronous case). Assuming a Gaussian distribution a 1σ value of $8*10^{-4}$ can be determined.

When tuning the accelerator to the non-isochronous mode a different behaviour was seen. While the scraper gap in the analysing system was moved, particles where removed from the beam even though the measured energy spread stayed constant. Unfortunately the analysing system also acts transversally, thus removing particles in the correct energy interval if they are too far off axis, which was obviously the case in the non-isochronously tuned machine. From that behaviour one can interpret the measured energy spread of $4.5*10^{-4}$ to be the 2σ value of a Gaussian (as 95 % of the particles were in that interval).

Concluding, the measurements show that going from an isochronous recirclation scheme (ϕ_s = 0° and r_{56} = 0 mm/%) to a non-isochronous scheme characterized by the parameters ϕ_s = -9.7° and r_{56} = -1.5mm/% decreases the energy spread of the beam from $8*10^{-4}$ to $2.3*10^{-4}$.

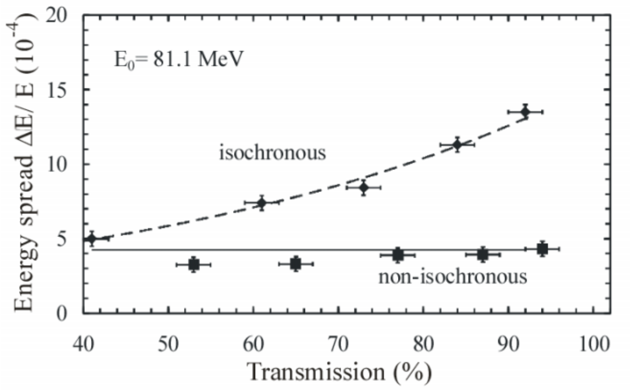

Figure 6: Measured energy spread in the isochronous and non-isochronous mode. For details see text.

To use it in daily operation additional measures have to be taken. First a simple diagnostics has to be developed in order to find the optimum working point. Currently, checking the synchronous phase requires the detuning of the machine which should be avoided when running experiments. Furthermore, the longitudinal dispersion r_{56} is a complex parameter of the magnetic lattice. Therefore a redesign is envisaged to separate the beam transport properties of the recirculation paths, allowing an easy way to adjust the longitudinal dispersion.

OUTLOOK

This paper describes two measures to decrease the beam energy fluctuations of the S-DALINAC. For detecting the long time drifts, we set-up a system which will give a feedback signal for the rf control loop. This feedback loop is currently designed and will be available within the next year.

The second measure taken concerns the initial energy spread of the beam. A simulation and an experimental proof shows that a non-isochronous recirculation scheme improves the beam quality by more than a factor of three. To use this advantage in daily operations additional modifications on the beam lines have to be made and new diagnostic tools are required. Some activities along these lines started recently.

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